PARAMETERS OF ELECTRODE IGNITION DISCHARGES IN SUPERSONIC PROPANE-AIR FLOWS

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Introduction

Effective solution of such aerodynamic problem as fuel ignition in ramjets at supersonic velocities is evidently impossible without an application of plasma technologies. In presented work we expose results of experimental and theoretical investigations of ignition process of supersonic propane-air flows with a help of transversal and longitudinal discharges.

Experimental setup

Experiments have been produced with an application of a wind tunnel of short action. Measurements were performed in supersonic air and air-propane flows with Mach number M = 2 under total pressures P_0 = 1 - 5 atm, stagnation temperature $T_0 = 300\,K$, vacuum chamber pressures p = 200 – 300 Torr; the propane mass fraction was about the stoichiometric one. Pulse transversal and longitudinal discharge with discharge currents I = 2 - 40 A, the pulse duration τ = 50 – 1000 μs and the pulse repetition rates f = 1 - 10 Hz were used. An aerodynamic channel includes the following parts: a device for preliminary mixing of air and propane (it is located before an inlet to Laval nozzle), dielectric channel that prevents possible electric breakdown to the metal body of the mixer, inletting block of electrodes to a channel, zone of a sudden expansion that prevents possible blocking of a channel after the mixture ignition, quartz pipe section where the mixture combustion and discharge plasma diagnostics take place.

Macroscopic **parameters of ignition discharge**

The influence on ignition of supersonic flow of two factors – pulse duration and discharge length were investigated.

The band of active radicals CH (λ = 431,5 nm) has been the most convenient for detection of air-propane mixture ignition [1].

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The dependence between the electric power density and the pulse duration of the pulsed transversal electric discharge, in which the ignition of the propane-air mixture flow was observed, has been determined [1]. The growth of electric power density results in reduction of the pulse duration. There is an electric power density threshold of ignition. Under the higher level of electric power density, shock wave generation is observed.

The value *of* τ is proportional to a discharge size along a flow [1] in studied range of parameters; it means that approximately constant value of energy inputted to a discharge $W_{thresh} \approx (IU\tau)_{thresh}$ corresponds to an ignition boundary.

Experimental results in these coordinates are presented in Fig. 1. One can easily see that a value of energy inputted to a discharge, which determines an ignition threshold, is weakly dependent on pulse duration, and in essence it determines the ignition. If it is so, then at constant value of a discharge current I and pulse duration τ there has to be a discharge length (determining U and W_{thresh} as well), below which the ignition will not occur. The longitudinal discharge allows varying a discharge gap length in case of fixed values of discharge current and duration.

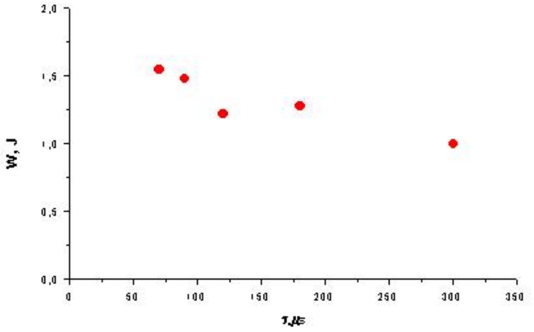

Fig.1. Threshold ignition energy value of supersonic propane-air mixture flow by a longitudinal and transversal discharges with respect to pulse duration. A point at τ = 300 μs corresponds to the longitudinal discharge.

P_0 = 4 atm, p = 200 Torr, M = 2.

Typical waveforms of CH radiation at different discharge lengths are presented in Fig. 2. One can see that the ignition does not occur at decreasing of the discharge length below some definite value. Boundary value of energy inputted to a longitudinal discharge is shown in Fig.1. It is close to the energy value necessary for ignition caused by the transversal discharge.

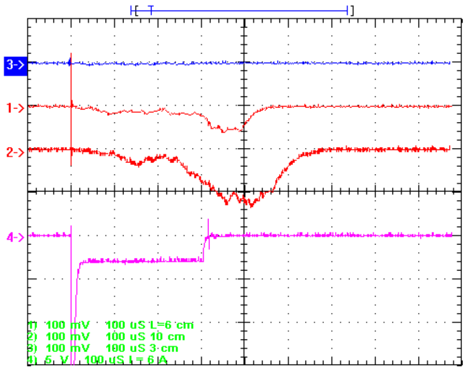

Fig.2. The influence of longitudinal discharge length L on ignition of supersonic propane-air flow. Curves 1,2,3 - waveforms of CH radiation, curve 4 – waveform of discharge current I.
p = 200 Torr, P_0 = 4 atm, M ≈ 2, I = 6 A, τ = 300 μs.

<u>Plasma parameters</u>

Plasma parameters of an electrode ignition discharges in supersonic propane-air flows were measured by probe and spectroscopic methods.

<u>Measurements of rotational and vibrational temperatures</u>

Intensity of second positive system in the air plasma drops sharply with pressure rise. Especially it is true in case of air-propane plasmas. For temperature determination in this case one has to use CN (0,0) and (1,1) bands intensities ratio. There are two questions that appear. Could one make a conclusion on a possibility of gas temperature measurements in conditions when a density of gas flowing out of a nozzle increases (i.e. in the case of full pressure increasing)? How does the temperature change in this case?

Dependence for fixed discharge current found during the experiment is presented in the Fig.3. Measurements were undertaken in the pulsed discharge at pulse duration 480 μs in the current generator mode. The jet off-design power was *n*=2. The radiation was detected from a region at a distance z ≈ 2 см from electrodes down a flow. Generally speaking, data obtained in the result of CN molecular bands relative intensities analysis at $P_0 > 1$ atm reflect an excitation temperature – the discharge vibrational temperature of molecules. It is easy to see that there is the excess of the temperature value determined by CN over the temperature value obtained by rotational temperature of the second positive N_2 system. It is naturally to expect that this difference has to decrease with increasing of pressure, so one can consider the temperature values found by CN to be the upper limit for the gas temperature. Then from the data presented in Fig.3 follows that the averaged value of the upper limit of the gaseous temperature at P_0 =4 atm is smaller than that at P_0 =1 atm.

Thus the temperature has a tendency to decrease when a density of gas flowing out of a nozzle increases (i.e. in the case of full pressure increasing) in difference to its dependence in motionless air.

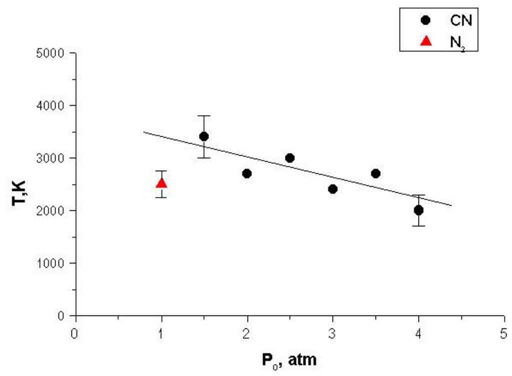

Fig.3. Full pressure influence on measured temperature of plasma of pulse longitudinal discharge in supersonic airflow

M = 2, n ≡ p^* / p = 2, I = 8 A, τ = 480 μs, L = 12 cm, z = 2 cm.

• - Vibrational temperature has been evaluated by the relative intensity of the molecular bands of CN ,

▲- Rotation temperature has been measured over relative intensities of lines of the rotational structure of the band (0;2) of the second positive system of N_2 .

It was shown earlier [1] and confirmed now that the neutral particle temperature is slowly decreasing along a flow. Thus, we can operate the mean gas temperature of main part of discharge. The correlation between this mean gas temperature and discharge current is shown in Fig.4.

One can easily see that the temperature in linear scale rises quickly at small currents (in the glow discharge mode) up to T=2000 K value and then its rise slows down. Such a behavior is practically opposite to the behavior of an electric field with a current.

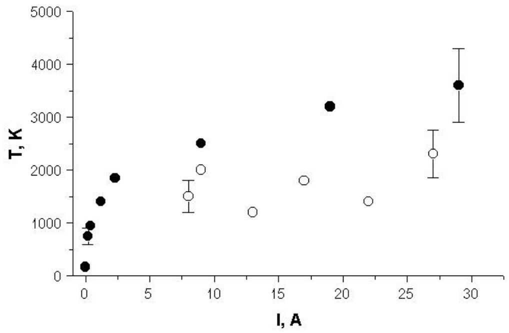

Fig.4. Mean gas temperature as a function of a discharge current.

M = 2, L = 12 mm , z = 1 cm.

• - P_0 = 1 atm, p = 40 torr, second positive system of N_2 .

o - P_0 = 4 atm, p = 200 torr, molecular bands of CN

Temperature drop is observed at full pressure increasing from P_0 =1 atm to P_0 =4 atm at all currents though this difference is insignificant at small currents.

In general we have to conclude that experimentally obtained gas temperature absolute values at high currents reach several thousands degrees though they stay smaller than the value of the electron temperature $T_e \approx 10^4$ K [3] calculated for these conditions.

So plasmas in conditions under the investigation is nonequilibrium one, it is insufficient to know the gas temperature value for determining of its conductivity, and direct measurements of the electron concentration are necessary.

Discharge plasma temperature value in air – propane mixture supersonic flow is significantly higher (Fig.5.) than those in the supersonic airflow, where it does not exceed 2000 K (see Fig.4).

Undoubtedly that such considerable temperature jump (with respect to air plasmas) can be explained only by the fact of propane – air mixture ignition.

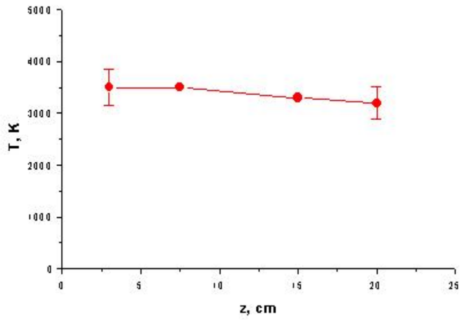

Fig.5. Temperature distribution in longitudinal discharge plasma in the supersonic propane-air flow along the axis of flow

p = 200 Torr, P_0 = 4 atm, M ≈ 2, L =10 mm, τ = 480 μs, I = 8 A.

Probe measurements

A double probe and PC-controlled probe measurement circuit with an opto-galvanic isolation was used for measurements of plasma density. Modes of probe operation in dense weakly ionized plasma flows under conditions of significant processes in the Debye layer have been studied primarily analytically on base of asymptotic analysis in extreme cases [2]. The modes of probe operation in the range of plasma parameters of igniting discharges are intermediate from the point of view of the analytical approach.

To studies of probe voltage current characteristics under realistic conditions to occur in plasma flows, we have carried out a cycle of computer simulations of one-dimensional probe diagnostic problems in a wide range of parameters of plasma flows.

Mathematical modeling plasma-probe interaction

Simulation of ion probe current in intermediate mode, when the probe ion current is defined either by processes in the Debye layer, or by the ambipolar diffusion were performed. For description of such modes of plasma-probe interaction, the quasi-neutral approximation is invalid in the Debye layer, and it is necessary to solve the Poisson equation. The Debye layer is nearly one-dimensional, as result the computations have been carried out in a one- dimensional approximation.

Computations for intermediate sets of ε≡, Re values ($\varepsilon = 10^{-8}$, $\mathrm{Re} = 10^5$ and $\varepsilon = 10^{-4}$, $\mathrm{Re} = 10^3$) been carried out.

The first case the Debye layer size amounts to 10% of the diffusion layer, i.e. the situation is close to the current saturation mode.

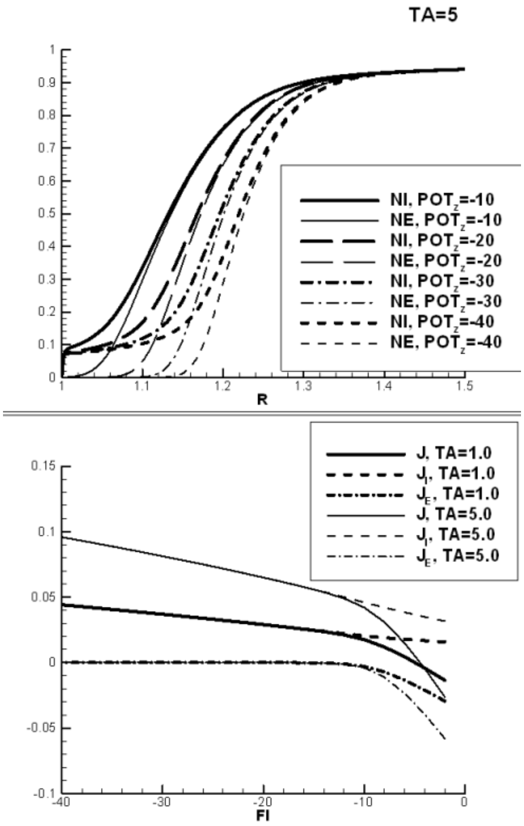

Fig.6. Spatial electron and ion density distributions and probe voltage current characteristic. $\varepsilon = 10^{-4}$, Re = 10^3.

In the second case the sizes of the Debye and diffusion layers (Fig.6) are close to each other; no quasi-neutral diffusion layer is formed.

The ion probe current grows with growth of the probe voltage due to growth of the Debye layer. Instead of saturation one can observe a fall of the voltage current characteristic slope for 3…5 times.

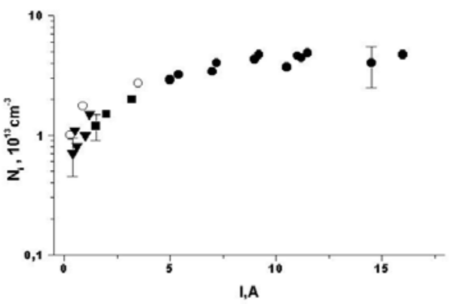

Fig.7. Plasma density versus discharge current.

P_0 = 1 atm, p = 40 Torr, z=3 cm.

Probe method: ○ –Ø 0,2 mm , ● –Ø 0,3 mm, ▼ –Ø 0,5 mm,

■ Stark- effect method

Results of charged particle measurements in the transversal discharge (Fig.7) obtained by probes and by Stark-effect method show that the concentration quickly increases at small currents and then its rising slows down. Absolute concentration values at $P_0 \approx 1$ and currents up to 30 A do not exceed 10^{14} cm^{-3}.

Simulation of an ignition discharge in a supersonic propane-air flow

Numerical modeling of a pulse-periodic and stationary electrode discharges as energy releasing zone in a supersonic airflow and air-propane mixture flow was made. Axisymmetric heat source model was considered for numerical simulation of the pre-mixed propane-air fuel gas ignition by the gas discharge in supersonic flow.

For description of the fuel gas ignition and consequent burning were used two chemical models: 5 species (C_3H_8, O_2, N_2, H_2O и CO_2) thermally equilibrium global model with single global reaction and 11 species (C_3H_8, O_2, N_2, H_2O, CO_2, H_2O_2, CO, H_2, OH, O, H) thermally equilibrium quasu-global chemical models with one global reaction and some detailed reaction [4].

The laminar flow is described by Navier-Stokes equations with additional source term in energy equation.

The effects of the heat source power, geometry and time expansion type on the ignition process were studied. The presented results are computed for experimental conditions: P_0 = 4 atm, T_0 = 300 K, M = 2 and stoichiometric composition of fuel mixture.

As example, the predicted for time t = 277 μs axial distributions of gas temperature and mole fraction of water vapor for some sets of heat source parameters are compared on Fig. 1,2. The time is measured from heat supply start.

The presented results are computed for total pressure P_0 = 4 atm, total temperature T_0 = 300K, Mach number M = 2 and stochiometric composition of fuel mixture with using of quasi-global chemical kinetics model. The specific source radius is 0.125 cm.

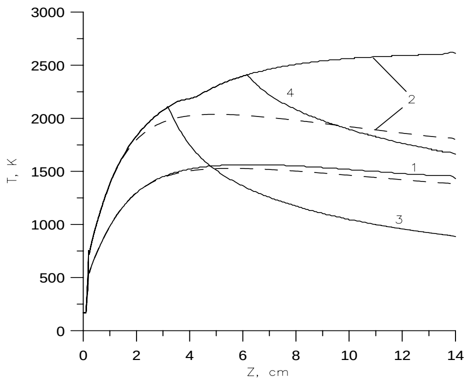

Fig.8. Gas temperature distributions along heat source axis.

1, 2 – the source time expansion along stream is unlimited, heat supply powers per unit length P $_h$ = 36 and 48 W/cm accordingly; 3, 4 - P $_h$ = 36 W/cm, heat source expansions is limited, - - - distribution in non-reacting gas flow with same heat supply.

Numbers 1, and 2 on Fig.8 denote cases when source time expansion along stream is unlimited and heat supply powers per unit length P_h = 36 and 48 W/cm accordingly. Numbers 3, and 4 denote results for P_h = 48 W/cm and heat source expansions limits are L =3.2 and 6.2 cm accordingly.

The temperature distributions in non-reacting gas flow with same heat supply are shown on Fig.8 by dotted lines. The distance Z on Figures is measured from heat source origin.

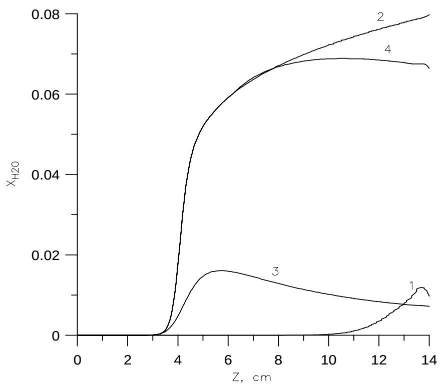

Fig.9. Water vapor mole fraction distributions along heat source axis.

1,2 – the source time expansion along stream is unlimited, heat supply powers per unit length P $_h$ = 36 and 48 W/cm accordingly; 3, 4 - P $_h$ = 36 W/cm, heat source expansions is limited.

The threshold specific power value, at which the ignition takes place and the threshold value of a discharge length were obtained.

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